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ECE DIAGNOSTIC OF HIGH TEMPERATURE ECRH HEATED PLASMAS ON FTU

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ABSTRACT

The Electron Cyclotron Emission (ECE) diagnostic on FTU tokamak is routinely performed with a Michelson interferometer with spectral range extending up to 1300 GHz. The diagnostic allowed accurate electron temperature measurements during the recent 140 Ghz Electron Cyclotron Resonance Heating (ECRH) experiments on FTU. Very accurate measurements have been performed on a wide range of electron temperatures and profile peaking. The ECE measurements have been compared with Thomson Scattering and with observations of X-ray spectra from highly stripped molybdenum ions. The suprathermal emission in these conditions has been studied.

I. INTRODUCTION

The Electron Cyclotron Resonance Heating (ECRH) is a fundamental method for fusion plasmas heating and control, and the ECE diagnostic plays a very important part in these plasma experiments. The well diagnosed FTU tokamak, with its characteristics of plasma density, magnetic field and operation frequencies, offers the opportunity to study the diagnostics performances in a reactor relevant ECRH scenario. In this paper, after an essential description of the experimental layout, we show and discuss the recent ECE measurements and the diagnostic performances during the last ECRH experiments on FTU tokamak, in which high temperature plasma (up to 8 KeV) and profile slopes (120 KeV/m) have been obtained and successfully diagnosed. The ECE spectra have also been analysed to study the occurrence of the suprathermal emission

II. EXPERIMENTAL SCENARIO

A. The ECE diagnostic of FTU

The ECE diagnostic on FTU consists of a fast scan Michelson interferometer, allowing electron temperature measurements with 5 μs resolution time[1]. The spectral range extends up to 1300 Ghz and the spatial resolution is 2 cm in both radial and vertical directions. In addition fast measurements are performed with a 12 channel ECE polychromator[2], with 10 μs resolution time and about 9 GHz of spectral resolution corresponding to a radial resolution of about 1.2 cm.

Both spectrometers operate with a InSb helium-cooled detector, with less than 2.5% non-linearity at 5 V amplified output signal. The maximum temperature signal of FTU plasmas is about 3 V, well below the non-linearity detector region. The unwanted 140 Ghz gyrotron radiation can jeopardize the broad-band Michelson spectra. To overcome this problem a QWG/RT notch filter manufactured by QMC has been inserted at the detector input. The filter has a transmission less than 2% at 140 Ghz and about 75% away from this frequency, while the HWHM is about 25 GHz. The absolute calibration has been performed with the new filter in place and refined using the magnetic field ramp technique obtaining the usual 4% uncertainty limit.[1,3]

B. The 140 GHz ECRH system

The FTU 140 GHz ECRH prototype system used in these experiments was based upon one Gycom Gyrotron GLGD-140-500 with 140 GHz frequency, 500 kW maximum achievable power and 0.5 s pulse length[4]. The outside launch antenna was made of a waveguide truncated at 16 cm from the nominal plasma edge and located in the horizontal midplane, perpendicularly to the toroidal field. The RF power was coupled to the plasma in the O-mode polarization, fundamental resonance (B=5 T). The vertical beam width for central resonance was about ±3 cm, while the deposition profile HWHM was ±2 cm in the normal operation conditions.

The beam power at the tokamak waveguide end was monitored with a high power calorimetric load designed for millimeter wave beams. A fast measurement of the power and polarization of the ECRH beam launched to the plasma was obtained with a directional coupler installed on the mirror of the last bend, before the launching antenna. Three low-gain probes (sniffers) have been installed in the tokamak to measure the RF power level residual after plasma absorption.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. High temperature plasmas measurements

Very high plasma temperature with respect to the normal FTU operational regimes, have been obtained by injecting the ECRH power in central resonance during the current ramp-up. In this phase the central energy transport is low, being the sawtooth instability not yet started. The plasma density is still ramping (from 3 to $6*10^{19}$ m^{-3} during the pulse), and the density profiles are flat before and during ECRH, with the flat-top region extending from 0.8 to 1.1 cm major radius. Fig. 1 shows a case with 360 KW ECRH power in which the maximum electron temperature was in excess of 8 KeV. The same picture shows that the sniffer signal is very high at the ECRH beam start, due to the poor optical depth τ of the plasma in this phase, and suddendly drops down when the plasma temperature reaches about 2 KeV, getting τ>2. The polychromator measurements showed that the discharge was sawtooth-free during the heating.

In almost all ramp-up heating shots a fast reconnection flattens the temperature, when it reaches high values. This effect, shown in fig. 2, is explainable by internal limits in the energy confinement in the ramping up phase. The polychromator signals show that after about 80 ms of RF heating a crash in the temperature occurs. After that a large sawtooth instability starts, enhancing the energy transport and keeping the profile flat. After the end of the gyrotron pulse, the sawtooth period and amplitude relax to the ohmic values.

The space resolved ECE measurements allow to study the electron temperature profile evolution (Fig. 3). After about 45 ms of ECRH the profile becomes very peaked reaching a maximum temperature of 8 KeV and a slope of about 115 KeV/m, a reactor-relevant value at these densities (max density 4.6*10-19 m^{-3}). This value is correctly resolved by the Michelson interferometer. In fact the measurable spectral slope is upper limited only at 230 KeV/m by the instrument resolution and the apodization window. The ohmic profiles during these phase, as observed in several ECRH-free twin plasma discharges, remains unchanged in shape with respect the 50 ms profile shown in fig. 3, and the Te reaches 1.5 KeV only.

B. The spectral distribution

The spectral distribution of the ECE has also been studied, to evaluate the suprathermal effects during the ECRH. The expected ECE spectrum has been calculated by means of the model discussed in Ref 5. The electron distribution function resulting from high power ECRH is computed by means of a 3-D bounce-averaged Fokker-Planck code, using the experimental density, temperature and electric field profile and the measured characteristics of the EC wave beam. The computed distribution function is then used to evaluate the fully relativistic dielectric tensor, which is used to compute the ECE spectrum. Both the ECRH and the ECE wave propagation are computed by means of a toroidal ray-tracing code. A wall reflection coefficient for the ECE radiation of the order of 0.7 is assumed.

As shown in fig. 4, the Michelson spectrum is in good agreement with the calculated one for the II, III and IV harmonics, clearly demonstrating that in spite of the low density values no suprathermal effects are detectable in this ECRH heated plasmas. The perpendicular launch (see II.B) enhances the energy absorption by the lower energy electrons. The remaining suprathermal population is poor and then easily re-absorbed by the distribution bulk.

C. Consistency checks

All the measured temperatures agree within the experimental errors with the Thomson Scattering (TS) data. For higher temperatures (> 5 KeV) as the ones shown in fig. 3, the TS uncertainties gets up to 20%, being presently the system optimised for lower Te. Nevertheless the profile peaking and shape are confirmed, even at 8 KeV (t=0.095 s in fig. 3).

The soft X spectra of L-emissions of highly stripped molybdenum ions (Mo^{29+} to Mo^{39+}) obtained with a low resolution rotating crystal spectrometer (fig. 5), allow to measure the electron temperature in an independent way. Detailed fully relativistic atomic calculations have been used to successfully explain these spectra.[6] Comparing the measured brightness of α , β and γ features, which are depending on the electron temperature, with the the theoretical curves, an assessment of the central mean temperature can be obtained (fig. 6). Due to the instrument resolution, the estimated temperature is a radial mean over the central plasma region. For ohmic case the central radial profile is quite flat and the value perfectly agrees with the ECE central plasma temperature Te(0) = 3.5 keV. For the ECRH case, the Te profile is very peaked and the estimated mean value is 6 keV, in agreement with Te(0)=8 keV.

IV. DISCUSSION

During the last FTU experimental campaign with 140 Ghz ECRH very interesting plasma conditions have been obtained and successfully diagnosed by the status-of-the-art ECE diagnostic system. The plasma RF absorption is full both in transient phase and flat-top heating, and the ECE spectra are suprathermal-free in these conditions. The attainable maximum electron temperature and Te profile slope have been reached in transient phase. Improved energy confinement regimes can be obtained by current profile and energy deposition optimization. A new ECRH system with four identical Gyrotrons and a very flexible launching system is almost completed and will be full operating in late 1998. This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

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FIGURE CAPTIONS

Fig. 1: Time evolution of the ECE electron maximum temperature and of the sniffer probe signal during a 360 KW ECRH pulse in shot #12658. The plasma current is ramping up from 200 to 680 KA and the central toroidal field is 5.4 T. The plasma density is linearly increasing from 3 to $6*10^{19}$ m^{-3} during the pulse.

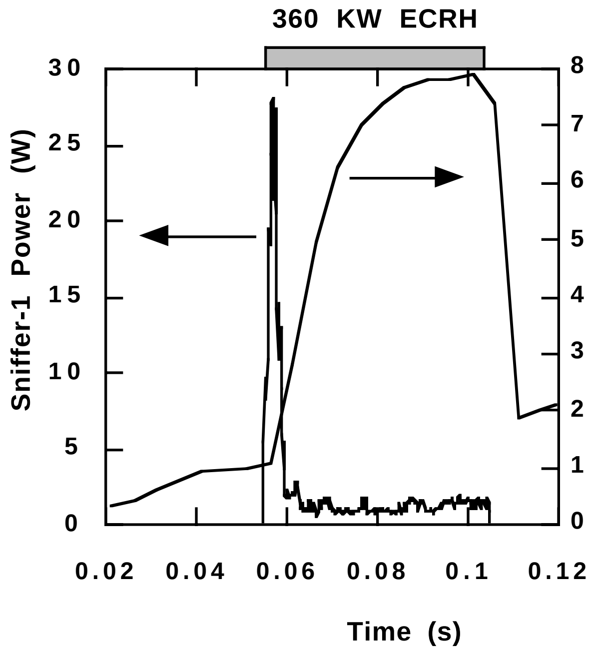
Fig. 2: Fast polyhromator signals at two different radial positions during the FTU shot #13119, with 210 KW ECRH starting at 55 ms. The maximum electron temperature from the calibrated Michelson interferometer, with 5 ms time resolution, is also shown. The sawtooth flattens the temperature profile, making the Te constant along the showed radii. The toroidal field is 5.3 T, plasma center is about 0.97 cm and plasma current and density are as in the fig. 1 data.

Fig. 3: Electron temperature profiles evolution from ECE Michelson, during the shot #12658. The ECRH starts at 55 ms, the 50 ms profile is then ohmic; the resonance center is located at 1 m major radius, as shown by the plotted ECE frequency profile. The plasma is strongly heated close to the center reaching a slope of about 115 KeV/m. In the same phase of the purely ohmic twin discharge, the temperature remains below 1.5 KeV and the profile shape is substantially unchanged.

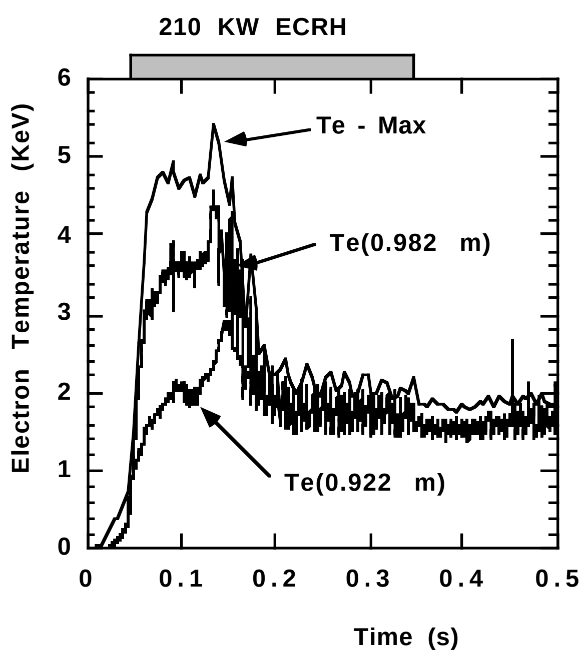
Fig. 4: ECE spectra as measured at 0.1 s by the Michelson interferometer (dashed line) and as calculated from the plasma parameters (solid line), for FTU shot #12658. Plasma current is 520 KA, central magnetic field 5.4 T and central plasma density $0.5*10^{19}$ m^{-3}. The harmonic number is indicated.

Fig. 5: Soft X ray emissions of highly stripped molybdenum ions (Mo29+ to Mo 39+) for an ohmic plasma (#12104, Te(0)=3.5 keV) and an ECRH heated one (#12658).

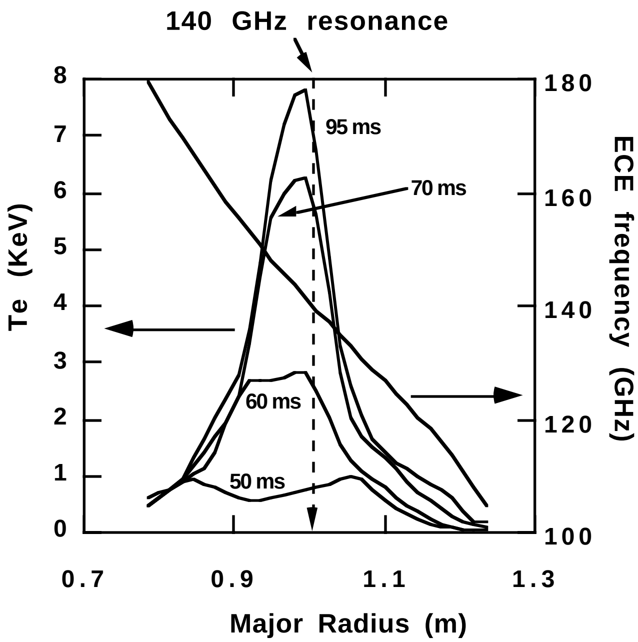
Fig. 6: Calculated brightness of the features α, β, γ, vs Te for an homogeneous plasma. The measured brightnesses and the corresponding electron temperatures estimates are also shown.

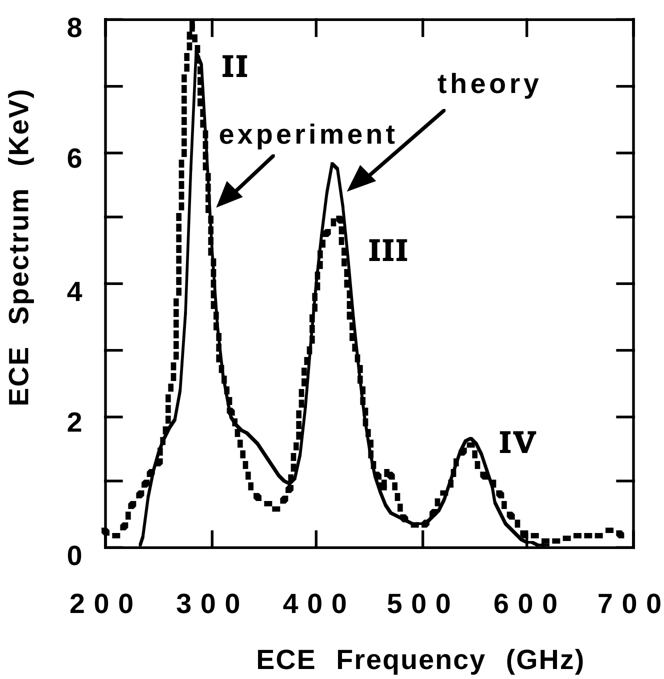


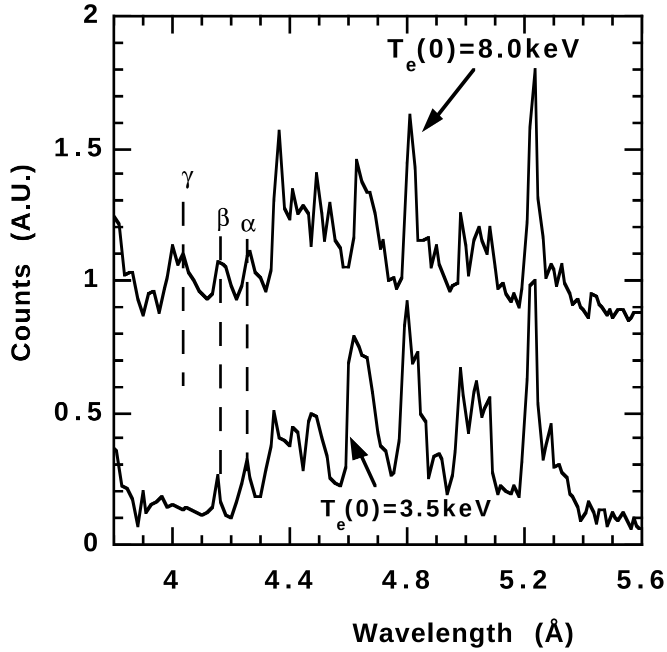
360 KW ECRH
Sniffer-1 Power (W)
Te-max (KeV)
Time (s)
0
5
10
15
20
25
30
0.02
0.04
0.06
0.08
0.1
0.12
1
2
3
4
5
6
7
8



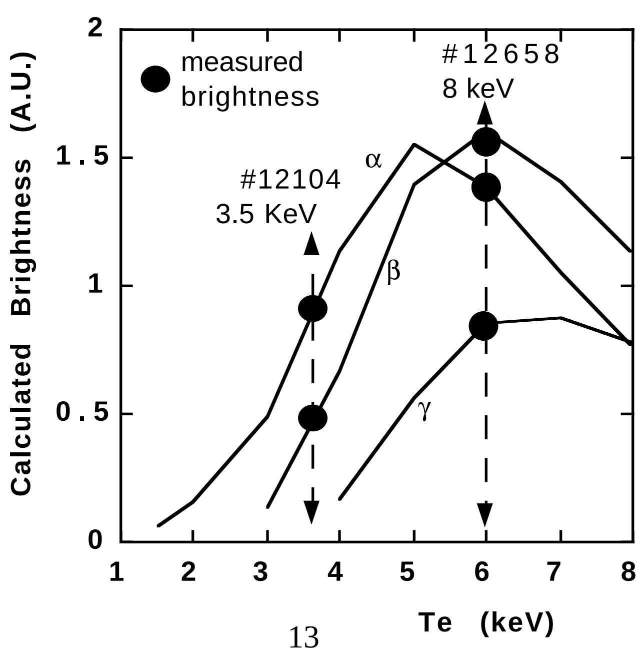
210 KW ECRH
Te - Max
Te(0.982 m)
Te(0.922 m)
Electron Temperature (KeV)
Time (s)
0
1
2
3
4
5
6
0.1
0.2
0.3
0.4
0.5


140 GHz resonance
95 ms
70 ms
60 ms
50 ms
Te (KeV)
ECE frequency (GHz)
Major Radius (m)
0.7
0.9
1.1
1.3
0
1
2
3
4
5
6
7
8
100
120
140
160
180


II
theory
experiment
III
IV
ECE Spectrum (KeV)
ECE Frequency (GHz)
0
2
4
6
8
200
300
400
500
600
700



2
1.5
1
0.5
0
Counts (A.U.)
γ
β
α
$T_e(0)$=8.0keV
$T_e(0)$=3.5keV
4
4.4
4.8
5.2
5.6
Wavelength (Å)



measured brightness
#12658
8 keV
#12104
3.5 KeV
α
β
γ
Calculated Brightness (A.U.)
2
1.5
1
0.5
0
1
2
3
4
5
6
7
8
Te (keV)